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Demonstrated Survivability of a High Temperature Optical Fiber Cable on a 1500 Pound Thrust Rocket Chamber

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1. ABSTRACT

A demonstration of the ability of an existing optical fiber cable to survive the harsh environment of a rocket engine was performed at the NASA Lewis Research Center. The intent of this demonstration was to prove the feasibility of applying fiber optic technology to rocket engine instrumentation systems. Extreme thermal transient tests were achieved by wrapping a high temperature optical fiber, which was cablized for mechanical robustness, around the combustion chamber outside wall of a 1500 lb Hydrogen-Oxygen rocket engine. Additionally, the fiber was wrapped around coolant inlet pipes which were subject to near liquid hydrogen temperatures. Light from an LED was sent through the multimode fiber, and output power was monitored as a function of time while the engine was fired. The fiber showed no mechanical damage after 419 firings during which it was subject to transients from 30 K to 350 K, and total exposure time to near liquid hydrogen temperatures in excess of 990 seconds. These extreme temperatures did cause attenuation greater than 3 dB, but the signal was fully recovered at room temperature. This experiment demonstrates that commercially available optical fiber cables can survive the environment seen by a typical rocket engine instrumentation system, and disclose a temperature-dependent attenuation observed during exposure to near liquid hydrogen temperatures.

2. INTRODUCTION

The application of fiber optics to rocket engine instrumentation is being studied at the NASA Lewis research center. Although fiber optic technology has seen many improvements in state-of-the-art during the past few decades, it lacks specific information on the survivability of many components in environments typical of rocket engines. Past work in this area has included an experimental investigation in which SSME instrumentation tests were performed on commercial optical fibers¹. As a result of this work, several commercially available coated optical fibers were determined to be capable of withstanding the extreme temperatures, thermal transients, vibrations and shocks typical of launch vehicle engine environments.

Before serious consideration can be given to fiber optic instrumentation systems for rocket engines, however, operation must be proven feasible not only in terms of survivability, but in ability to pass data with sufficient integrity. This integrity not only refers to an acceptable attenuation level, but also to the repeatability of any losses which may be incurred. The work described in this paper was intended to provide a demonstration of the ability of an optical fiber cable to

survive operation in an integrated engine environment, and to identify any significant loss trends requiring further research. To accomplish these goals, a single high temperature optical fiber cable was wrapped around the combustion chamber and liquid hydrogen inlet pipes of a 1500 pound thrust rocket chamber. The chamber was fired in a cyclic manner for five test runs, exposing the fiber to an extreme environment which included temperature transients from approximately 30K to approximately 350K, and continuous exposure to near 30K. The fiber showed no signs of damage after completion of the test firings, but exhibited attenuation related to the extreme cryogenic temperature exposure.

3. ENGINE DESCRIPTION

The test bed engine used for this demonstration is described in detail in reference 2. The engine is a 1500 pound thrust, subscale rocket engine test apparatus which is used to study rocket chamber liner fatigue life. Figure 1 shows the engine configuration which consists of an injector, a plug centerbody and a combustion chamber. Gaseous hydrogen (GH₂) and liquid oxygen (LOX) are injected into the combustion chamber and accelerated through the sonic throat which is formed by the plug centerbody. This centerbody is cooled with water to protect it from the extreme heat flux associated with the sonic region of the engine throat. Liquid hydrogen (LH₂) is used to cool the combustion chamber wall which is made of a highly conductive copper alloy.

The engine is fired in cycles: each cycle lasting 3.5 seconds and producing temperature transients in the combustion chamber wall as shown in figure 2. A cycle is begun by igniting the GH₂ and LOX and combustion is ceased by shutting off the flow of fuel and oxidizer to the combustion chamber. The chamber wall is cooled with LH₂ to approximately 30K before the next cycle is ignited. During this test, combustion chamber pressures reached 4137 KN/m² (600 psia) with a propellant mixture ratio (oxidizer-to-fuel) of 6.0.

4. TEST SETUP

A single optical fiber was used for the duration of all tests. This fiber was a Titanium Carbide-coated, 100/140 micron fiber with a silica core and cladding and was cablized with a cable design made of Teflon-reinforced Kevlar. This cable design provides mechanical stability and is rated to 250C.

4.1 Thermal transients

For the thermal transient data, fibers were wrapped around the backside wall of the plug nozzle engine and subject to 419 cycles. As shown in figure 2, each cycle produced a temperature transient at the backside wall from approximately 30K to approximately 350K, and lasted for 3.5 seconds.

4.2 Cryogenic temperatures

To expose the fiber to longer duration cryogenic temperatures, it was wrapped around LOX and LH2 inlet pipes. This was done both in conjunction with the thermal transient tests (so part of the fiber was exposed to temperature variations from cryogenic to over 300K) and in an isolated test.

During 163 of the thermal transient firings, part of the optical fiber was wrapped around LOX and LH2 inlet pipes in addition to the combustion chamber outside wall. Total time exposed was greater than 570 seconds. The fiber was then wrapped tightly around the LH2 inlet pipe only. Insulating cloth was wrapped around the pipe and fiber, which kept the temperatures near that of liquid hydrogen (hydrogen boils at about 20K), and the engine fired for 121 additional cycles. Exposure time during the second set of cryogenic tests was greater than 423 seconds for a total exposure to near liquid hydrogen temperatures of at least 993 seconds.

4.3 Instrumentation

An LED driven by a signal generator, was used to provide approximately 100 microwatts of light power to the fiber. Ambient temperature fiber cable carried the signal between the test stand and control room, requiring two connectors at approximately 1 dB loss per connector. The high temperature cable was used in the test stand area where environmental conditions were no longer ambient.

A *p-i-n* photodiode was used to sense optical output power. This signal was amplified and sent to a digitizing oscilloscope and a strip chart recorder, where optical output power was recorded as a function of time. Engine chamber pressure was recorded synchronously with the optical signal to provide a reference to the engine cycle, which could be correlated to outside wall temperature.

5. RESULTS

A total of five different engine test runs were performed: during four of which the fiber cable was subject to extreme thermal transients, and during one the cable was subject only to cryogenic temperatures. Figure 3 shows the maximum power attenuation incurred during each of these firings, ranging from 4 to 5.5 dB when the fiber was wrapped around the combustion chamber. Losses were much higher, as shown for test number five, when the fiber was wrapped around the LH2 inlet pipes only. This is due to the smaller diameter of the pipe, and to the fact that the fiber was only subject to cold temperatures and not warmed up during the firing. Although the optical signal throughput exhibited some losses as the engine cycled, post test inspection revealed no observable signs of damage to the fiber cable. In both the thermal transient tests, and the cryogenic-only test, the signal recovered fully as the engine and fiber cable warmed up to room temperature, verifying that no permanent damage had been incurred.

5.1 Thermal Transients

Figure 4 shows the typical shape of the optical power profile observed over an engine cycle. The peak to peak power loss observed over each cycle, was measured as the maximum power output minus the minimum power output, and ranged from 0 to 10 microwatts. These losses were repeatable over the series of firings. This is shown in figure 5 which displays peak-to-peak power loss, normalized to peak power, for each of the 256 engine cycles when the fiber was wrapped around the outside wall of the combustion chamber only.

The shape of the loss curve in figure 4 is typical of each firing. The optical signal decayed for the first part of the firing, decayed at a slower rate or actually increased in the middle, and continued to decrease to the end of the cycle. This is consistent with the engine cycle behavior. At the beginning of the engine cycle, the chamber wall is chilled to approximately 30K, which begins cooling the fiber cable and inducing losses. As the engine is fired, it vibrates (which may induce extraneous micro- and macro-bend losses) but at the same time heats up the outside of the chamber wall according to figure 1. This serves to heat up the fiber cable and recover some of the losses incurred during the cool-down. In the latter part of the cycle, the combustion is ceased and the chamber is again cooled down to near 30K, again chilling the fiber cable and inducing losses. A reasonable explanation for the overall downward slope of the curve would be that the fiber is slowly reacting to the extreme cryogenic temperature exposure during the duration of the test, and reacting more quickly to the 3.5 second temperature spike caused by each firing. The resulting characteristic is a loss curve similar to figure 6 due to the cryogenic exposure of the curved fibers, with small gains in optical power occurring in each cycle, caused by the warming of the fiber.

5.2 Cryogenic Temperatures

Figures 6 and 7 show the behavior of the optical signal during the chill-down and warm-up (return to room temperature) of the engine test stand. Figure 6 shows the loss incurred during each test when liquid hydrogen flowed through the LH2 pipes and combustion chamber to chill the system. The optical signal dropped as much as 2.7 dB before engine firings began and is shown in figure 7 to recover fully after the test completion when the cable is allowed to return to room temperature. Several data points in figure 7 display a negative power loss, which is due to drift in electronics during the test duration, and the limited accuracy of the analog chart recorder. These plots serve to isolate cryogenic temperature as the major cause of the attenuation observed in the optical power throughput during the engine testing. Each test varied in several ways from the other tests, which can explain the discrepancies in the curves in figures 6 and 7. These variations include how tightly the fiber cable was wound, and the length of fiber cable in direct contact with either the highly conductive copper chamber wall or the stainless steel coolant pipes.

6. CONCLUDING REMARKS

A successful demonstration has been performed where a commercially available, high-temperature optical fiber cable survived the integrated harsh environmental parameters of a rocket engine. The cable did not endure any physical damage during over 419 thermal cycles from 30K

to 350K, and over 993 seconds of engine operation while the fiber was exposed to near liquid hydrogen temperatures. Losses incurred during engine firing and exposure to liquid hydrogen temperatures were recovered fully when returned to room temperature. These results provide favorable evidence toward the application of fiber optic technology to rocket engine instrumentation systems. The severe cryogenic environment caused excessive (greater than 3 dB) attenuation in the optical power throughput. These losses must be characterized in order to be predictable, and to facilitate the design and evaluation of referencing schemes. The variation in the optical signal caused by thermal cycling was not excessive, and was repeatable. This type of signal modulation might be compensated for by using wavelength- or time-domain referencing.

7. REFERENCES

1. Delcher, R., Dergevorkian, A., and Barkhoudarian, S., "Fiber Optics for Adverse Space Environments," *AIAA Paper 89-2416*, 25th Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.
2. Kazaroff, J., Jankovsky, R., and Pavli, A., "Hot Fire Test of Subscale Tubular Combustion Chambers," *NASA TP 3222*, 1992.

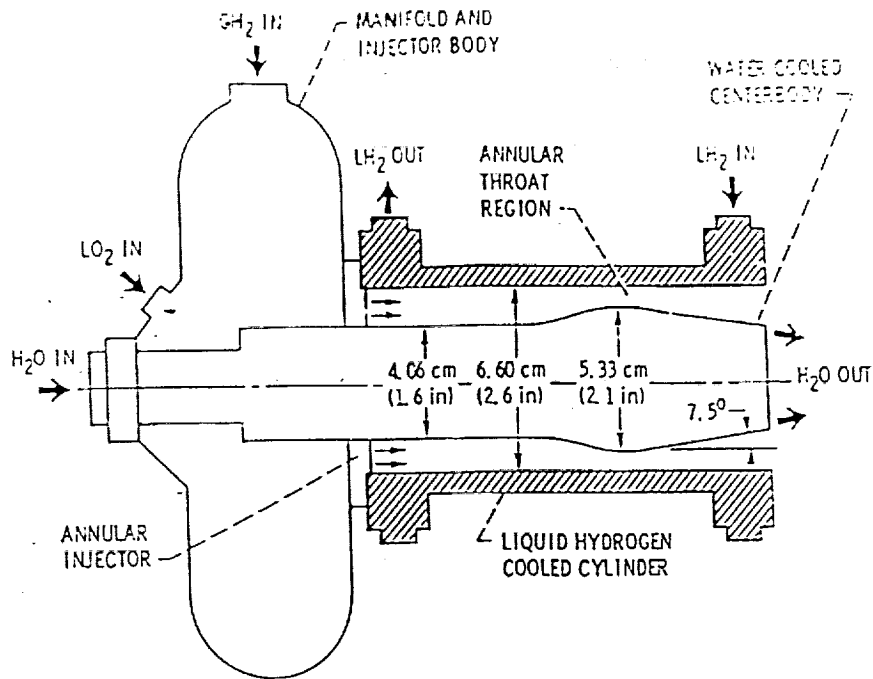


Figure 1. Schematic of subscale rocket engine thrust chamber assembly (ref. 2).

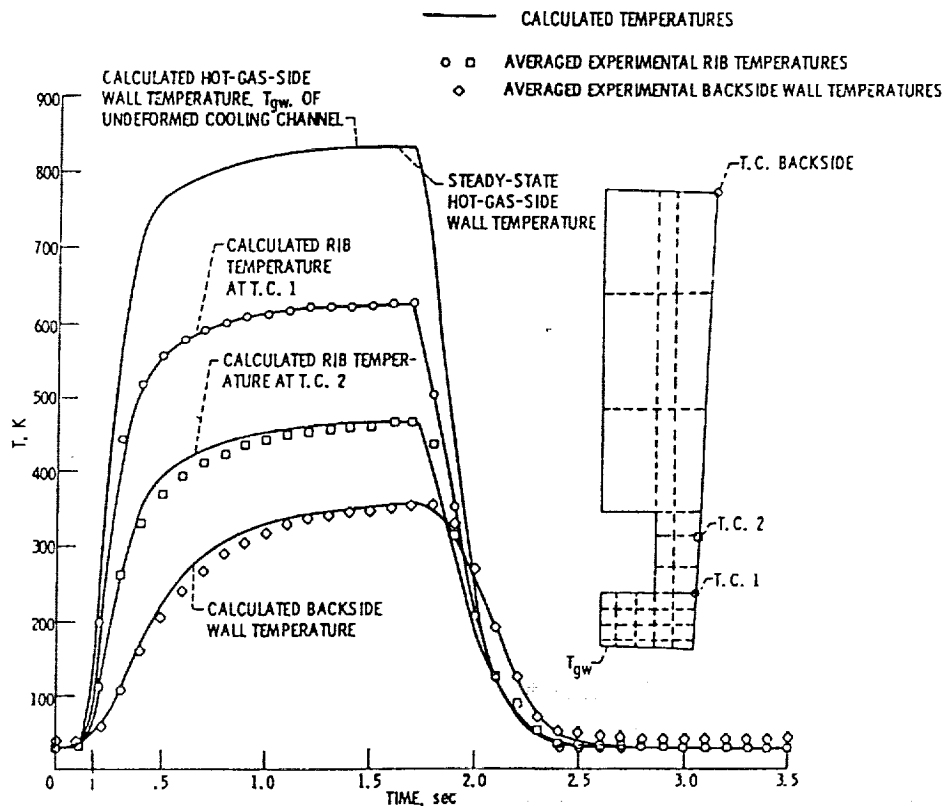


Figure 2. Temperature of the chamber wall during one engine cycle (ref. 2).

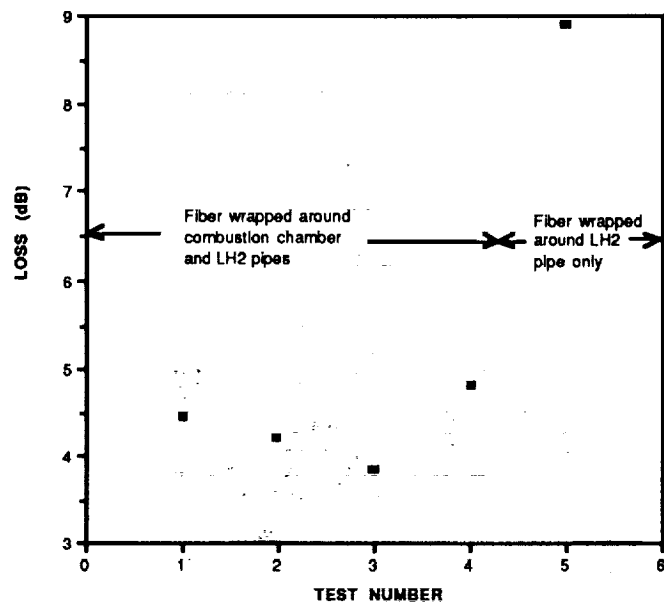


Figure 3. Maximum power loss incurred during each test firing.

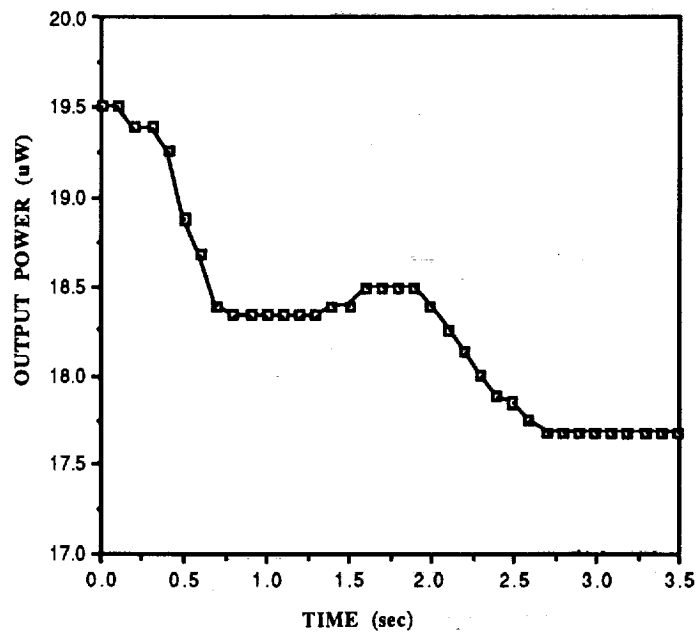


Figure 4. Typical power profile during engine cycle.

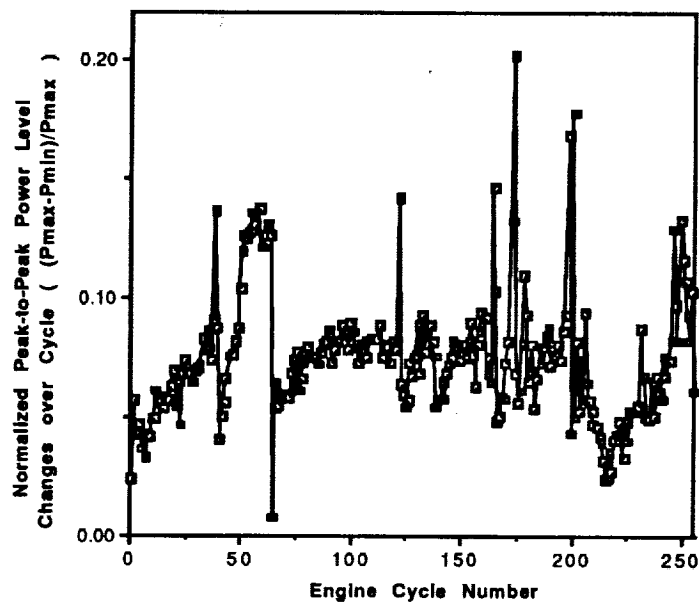


Figure 5. Repeatability of attenuation curves due to engine cycling.

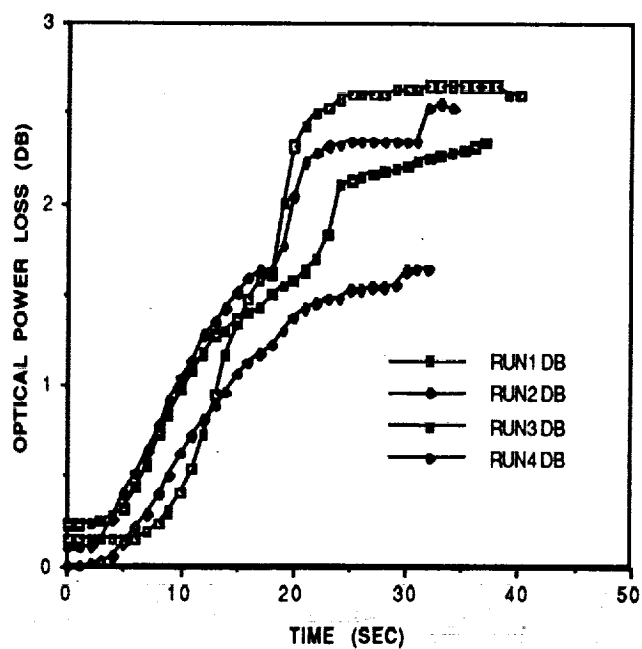


Figure 6. Loss of optical throughput during cooldown (flow of liquid H₂ through cooling passages).

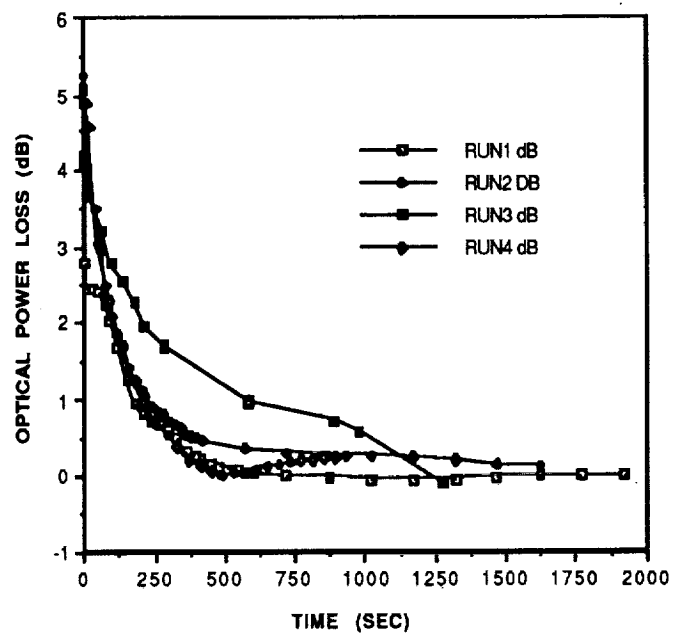


Figure 7. Recovery of optical signal after completion of testing.

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